Gradient Representations and the Perception of Luminosity

Matthias S. Keil*
Basic Psychology Department, Faculty for Psychology, University of Barcelona (UB), Passeig de la Vall d'Hebron 171, E-08035 Barcelona (Spain)
(Dated: February 2, 2008)

The neuronal mechanisms that serve to distinguish between light-emitting and light reflecting objects are largely unknown. It has been suggested that luminosity perception implements a separate pathway in the visual system, such that luminosity constitutes an independent perceptual feature. Recently, a psychophysical study was conducted to address the question whether luminosity has a feature status or not. However, the results of this study lend support to the hypothesis that luminance gradients are instead a perceptual feature. Here, I show how the perception of luminosity can emerge from a previously proposed neuronal architecture for generating representations of luminance gradients.

Keywords: Luminance, gradients, brightness, lightness, luminosity, surfaces, Ehrenstein, Chevreul, glow, fluorent, Mach, highlight

I. INTRODUCTION

Under daylight illumination conditions, looking at a television or computer screen rarely produces the sensation that displayed items are light-emitting, although each pixel of the screen emits light ([41], with references). But to perceive objects as being luminous, it is not necessary to have a physically source of light emission. Halos were used by artists since a long time as a means to create luminosity effects in their paintings ([41], with references). When a region is painted with a halo surrounding it, then one perceives this region with enhanced brightness, or even as glowing, without physical light emission being present. Thus, the perception of glow *can* be evoked on (light reflecting) paper or canvas, and text or pictures being displayed on a (light emitting) computer screen are *not necessarily* being perceived as luminous.

In other situations perception and physics are not divergent. For example, the sun is always perceived as light emitting, and so are stars at night. In such situations, the strong contrast between light sources and background may provide the key factor to the perception of luminosity [3, 4].

A recent fMRI study has identified a region in the brain which seems to be associated with the perception of luminosity [27]. In this study, different configurations of the glare effect display ([5, 23, 40]; figure 5, top row) were presented to human observers. The results of the study were indicative to that luminosity might constitute a perceptual feature much like contrast, orientation, motion, or faces. The question about whether luminosity is a perceptual feature or not motivated a corresponding psychophysical study [7]. The study was based on the idea that perceptual features are distinguished from other object properties by being processed in a more efficient way. This means that visual features consume less attentional resources than non-features [18], what is reflected in, for example, "pop out" effects. A visual search paradigm such as the one used in the study of [7], therefore can serve to distinguish features from non-features. Unexpectedly, the results of Correani *at al.* are compatible with that *luminance gradients* instead of luminosity are a visual feature. Several authors have already formulated the hypothesis that luminance gradients are involved in the perception of luminosity [23, 40, 41, 42], as there is evidence that luminance gradients can influence lightness perception under certain circumstances.

I therefore asked whether a recently proposed theory for the perception of luminance gradients ("gradient system") could account for the just-described observations. The gradient system has been successful in quantitatively predicting available data on Mach bands [22]. It furthermore provided an account for Chevreul's illusion in terms of luminance gradients [20], and in addition is capable of real-world image processing.

In this work I will show how spatial configurations of luminance gradients can interact to produce the perception of luminosity in the absence of physical illuminants. The results presented here also contribute to the further understanding of how luminance gradients interact with lightness computations and brightness perception, respectively. Specifically, representations of luminance gradients provide a straightforward explanation of "self-luminous grays" [41, 42], and why it is that perception of luminosity is independent from lightness anchoring.

II. INTRODUCING THE GRADIENT SYSTEM

This section provides an overview over important characteristics of the gradient system. A more detailed description of it, as well as its formal definition, can be found in [20] and [22].

*Electronic address: matsATcvc.uab.es; threequarksATyahoo.com; AT=@

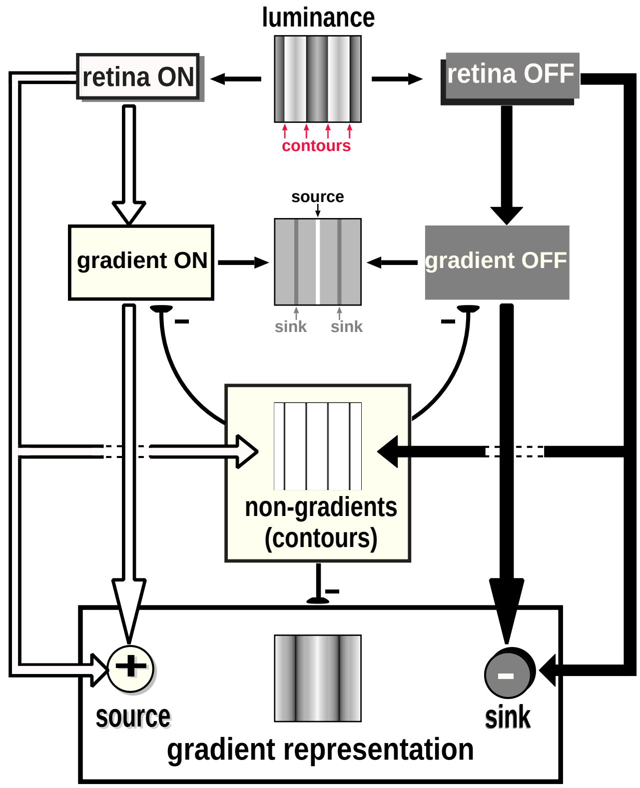


FIG. 1: **Functional overview over the gradient system.** A *notched square wave grating* (or briefly "notch grating") is used for illustration of the processing stages. A notch grating is a square wave with notches being centered at each luminance step, and luminance decays (for the bright stairs) and increases linearly (for the dark stairs), respectively, to a common luminance level (the luminance profile is shown in figure 2). This means that the faint lines centered at each step have the same intensity value, yet they are perceived with different brightness. See section II B for a detailed explanation of the processing stages.

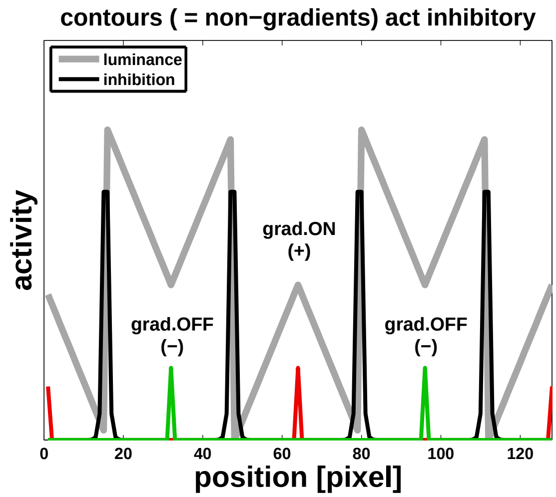


FIG. 2: **Gradient enhancement and contours (= non-gradients).** The *notched square wave grating* (or briefly "notch grating", legend label "luminance") is a periodic spatial pattern composed of step-like changes and linear luminance gradients (the notches). Contours are detected at the step-like changes in luminance. Contours are related to surface processing, and thus should be suppressed in gradient representations. In the gradient system, the suppression is executed by contours acting inhibitory (see legend label). This *non-gradient* inhibition leaves just those activity patterns in retinal channels which correspond to smooth changes in luminance (*gradient ON* activity "(+)", and *gradient OFF* activity "(−)"; c.f. figure 1). During the creation of a gradient representation, gradient ON and OFF patterns eventually act as *sources* and *sinks*, respectively. Depending on whether sources and sinks correspond to a linear luminance gradient (as shown here) or not, a gradient has to be explicitly be generated or not, respectively (see figure 3).

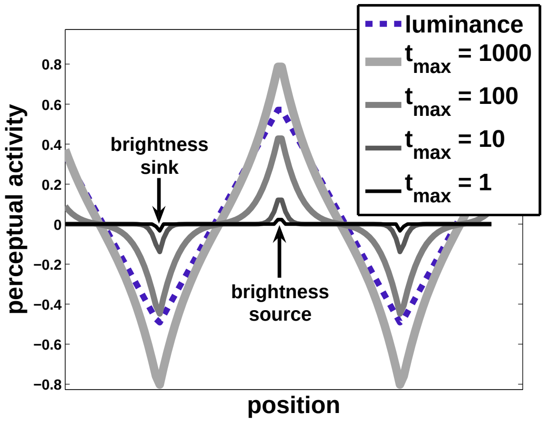
A. Motivation

The original motivation for proposing representations of luminance gradients was that they are of different utility for object recognition. It is known, for example, that they may aid to *(i)* recover three-dimensional information to compute surface shape (shape from shading, e.g. [29, 33]), *(ii)* to resolve the three-dimensional layout of visual scenes (e.g. [2, 24]), *(iii)* to identify material properties of object surfaces (e.g., mat versus glossy), and are therefore complementary to lightness computations (lightness is associated with surface representations).

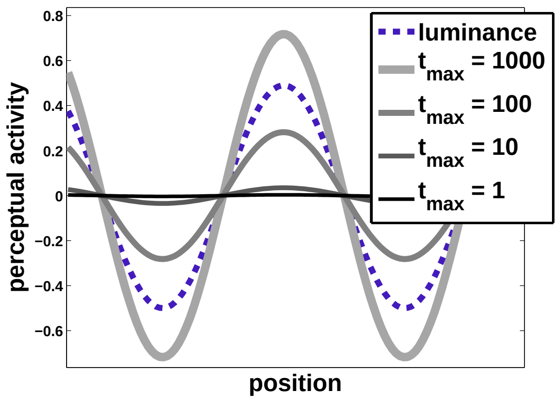
In situations, however, it may happen that luminance gradients rather would interfere with the goal of generating invariant surface representations, and thus disrupt lightness constancy. (Invariant surface representations are mandatory for robust object recognition). In natural scenes, specular highlights, cast shadows, and slow illumination gradients are often superimposed on object surfaces. In such cases, luminance gradients must be suppressed in surface representations for establishing lightness constancy. Nevertheless, it has been demonstrated recently that humans use cues such as shadows, shading and highlights for segregation of object surfaces [9]. Thus, lightness constancy implies discounting "gradient features" on the one hand, yet on the other hand they are used by humans to achieve a more reliable segregation of figural regions from the background.

Taken together, luminance gradients contain different information, which cannot be interpreted by bottom-up mechanisms. Without segregating them from surfaces, surface representations would vary as a function of illumination conditions and scene layout. Notice that such a merged representation would necessitate segregation anyway, as lightness constancy is not interrupted by specular highlights [36], and human object recognition seems to work reliably for most illumination conditions and scenes.

Having separate representations for surfaces and



(a)



(b)

FIG. 3: **Linear and nonlinear luminance gradients.** (Both plots show activity profiles of two-dimensional representations at different times – see legend). Linear luminance gradients *(a)* are processed by the gradient system differently to nonlinear gradients *(b)*. In the former case, an activity gradient has to be explicitly generated by lateral spread of activity between a brightness *source* and a brightness *sink* (a matter of fact, a brightness source is equivalent to a darkness sink, and a brightness sink is equivalent to a darkness source). Sources and sinks may be localized activity patterns as in *(a)* (where they are indicated by arrows), but be also spatially more extended as in *(b)* (i.e., for nonlinear luminance gradients). In the initial gradient representation, sources and sinks of nonlinear gradients are just a low-activity version of their final representation. Thus, representations for nonlinear luminance gradients are produced by only amplifying the initial activity pattern, similar to a standing wave with increasing amplitude. The corresponding luminance displays and their gradient representations in 2-D are shown in figure 16.

gradients, however, has the advantage that gradient representations could be dynamically linked to lightness computations [38]. In this way, mechanisms for object recognition could utilize or suppress corresponding information, what could contribute to increase robustness.

B. How it works

The gradient systems is a hypothetical neuronal circuit, and its main processing stages are shown in figure 1 (see also figure 1 in [22]). The retina constitutes two pathways, which are related to brightness ("ON-channel"), and darkness ("OFF-channel"), respectively. A high-resolution boundary map is produced by processing information from both channels[43]. "High-resolution" is to say that only the finest scale is considered. At a cortical level, boundary maps are usually regarded as demarcating surface representations thus defining surface shape. Because contours define surfaces, but not gradients, they are referred to as *non-gradients* within the gradient system. Non-gradients act always inhibitory (figure 2).

In the first step of gradient processing, gradients are enhanced by suppressing ON- and OFF-activity at non-gradient positions. The result of this process can be conceived as "retinal activity maps with erased contours" ("gradient ON" & "gradient OFF" in figure 1).

In the second step, retinal ON-activity and gradient ON-activity provide excitatory input to the site labeled by "+" in figure 1. Analogously, OFF-activity from retina and gradients act inhibitory on the site labeled by "−"[44]. Excitation and inhibition is tonic or *clamped*, what means that activity is actively generated at "+" and "−. In addition, activity spreads laterally: Activity values with positive sign from "+", and negative values from "−". Silent (or shunting) inhibition (reversal potential equals resting potential that is zero) exerted by non-gradient features during activity propagation quickly suppresses boundaries, while at the same time gradient activity is further enhanced. As a consequence, *sources* and *sinks* are dynamically created[45]. Because of lateral propagation processes, activity gradients will eventually form between sources and sinks (but see figure 3). This latter process is referred to as *clamped diffusion*[20, 22].

Silent non-gradient inhibition imposes a further important constraint on the creation of gradient representations: Gradients cannot spread beyond a surface over which they were originally superimposed. This constraint also implies that activity gradients could form between a source and a site of active non-gradient inhibition, but also between a sink and a site of active non-gradient inhibition. Such behavior occurs, for example, with the *notched square wave grating* ("notch grating", figures 1, 2, 14 & 15).

The gradient system generates representations of linear luminance gradients by lateral propagation of activity between a brightness source and a brightness sink. At equilibrium, an activity gradient has formed between source and sink (figure 3*a*).

On the other hand, nonlinear luminance gradients, such as sine wave gratings, need not to be explicitly created as it is the case with linear gradients. Rather, the initial activity pattern is only amplified (figure 3*b*). Notice that representations of linear and nonlinear gradients are

generated by the same mechanism, that is clamped diffusion.
Summarizing, there are three components which influence in the generation of gradient representations. *(i)* Brightness sources are created from the retinal ON-channel, and their activity is related to “brightness”. Brightness sources constantly generate activity with positive sign. This activity propagates laterally. *(ii)* Brightness sinks are the counterpart of brightness sources, and originate from the retinal OFF-channel. Brightness sinks are are identical with darkness sources, because they generate negative-valued activity. By the same arguments are brightness sources identical with darkness sinks. If a stimulus only contains luminance gradients, then only brightness sources and brightness sinks will influence in the formation of gradient representations, where activity gradients will form between sources and sinks (or between brightness sources and darkness sources). *(iii)* If the stimulus, however, contains surface structures, silent non-gradient inhibition will be evoked, which strictly speaking acts as an activity drain for both brightness and darkness activity. Non-gradient inhibition, however, does not actively generate activity. To avoid name clashes, the terms “sources” and “sinks” are exclusively reserved for brightness sources and brightness sinks, respectively. The term “drain” is used to refer to activity dissipation because of non-gradient inhibition. *(iv)* Representations of linear and nonlinear luminance gradients are generated by the same mechanism (clamped diffusion).

III. MATERIAL AND METHODS

All results were generated with the implementation of the gradient system as described in [20], and [22], respectively. All parameter values and numerical methods were also the same for the present study as before. Simulations were carried out with a Matlab environment (R2006b) on a Linux workstation. If not otherwise stated, gradient representations were evaluated at $t_{max} = 1000$ iterations. For the figures 8, 9 and 13, gradient activity was averaged across the positions of the central square of the input (see figure 4). Spatial averaging was carried out separately for brightness (i.e., positive values) and darkness (i.e., negative values), respectively. In both of the last figures, the figure label “perceptual activity” means that the absolute value of average darkness was subtracted from average brightness at each data point. In figure 12, only brightness activity is shown, as the first data point of all curves (corresponding to luminance zero of the central square) gave -0.0022 for computing *average brightness* minus *average darkness*, and the abscissa was scaled logarithmically. Each of the images in figure 5 and 7 showing gradient representations were normalized individually in order to improve the visualization. For the figures 10 and 11, the image size was 256×256 pixels. For the rest of the simulations, luminance displays were of size 128×128 pixel. Luminance values were in the range from 0 (black) to 1 (white).

IV. RESULTS OF SIMULATIONS

A. The glare effect

In the present study, the glare effect display was systematically modified and corresponding responses of the gradient system were studied. The original glare effect (as introduced in [40]) is shown in the first image of figure 4. It consists of a chessboard image (*carrier*), in which four black squares were substituted by luminance ramps (*inducer squares*). The white field of the chessboard which is surrounded by the luminance ramps is the *target square* or *central square*. Notice that the ramps are linear gradients. Depending on the spatial arrangement of the luminance ramps with respect to the central square, it is perceived as being light-emitting in the *glow* setup (all images in figure 4, first image in figure 5). If the luminance ramps are arranged according to the *scrambled* setup or the *halo* setup (figure 5), then one cannot observe any brightness enhancement of the central square [7, 27]. Similarly, no brightness enhancement occurs in the *control* configuration, where the four inducer squares are set to a homogeneous luminance value - the mean value of a inducer square.

B. Simulations of different setups

The bottom row of figure 5 (“gradients”) shows gradient representations which have been generated from the images shown in the first row (“setup”). The gradient representation produced by the *glow* setup shows a neon-like square that is located along the contours of the central square. Because linear gradients (i.e., luminance ramps) were used as inducers, each side of the neon-square actually corresponds to a bright Mach-band [28]. In the course of clamped diffusion dynamics (second stage of the gradient system), the Mach bands implement brightness sources, from which activity spreads laterally to generate representations of luminance ramps (the dark Mach band constitutes the corresponding brightness sink). In the *glow* setup, the four Mach bands are situated around the central square, thereby forming a closed region where gradient brightness accumulates over time (figure 6*b* & 10). In other words, although there is no (physical) luminance gradient present across the central square, it is “tagged” with strong gradient brightness. Because activity does not dissipate (i.e., there is no drain or brightness sink across the target), and because brightness sources constantly generate activity, overall brightness activity eventually grows higher than darkness activity. Thus, “perceived brightness” is higher than “perceived darkness” in the final representation[46], and the central square will appear luminous.
In the *control* setup, no luminance gradients are present.

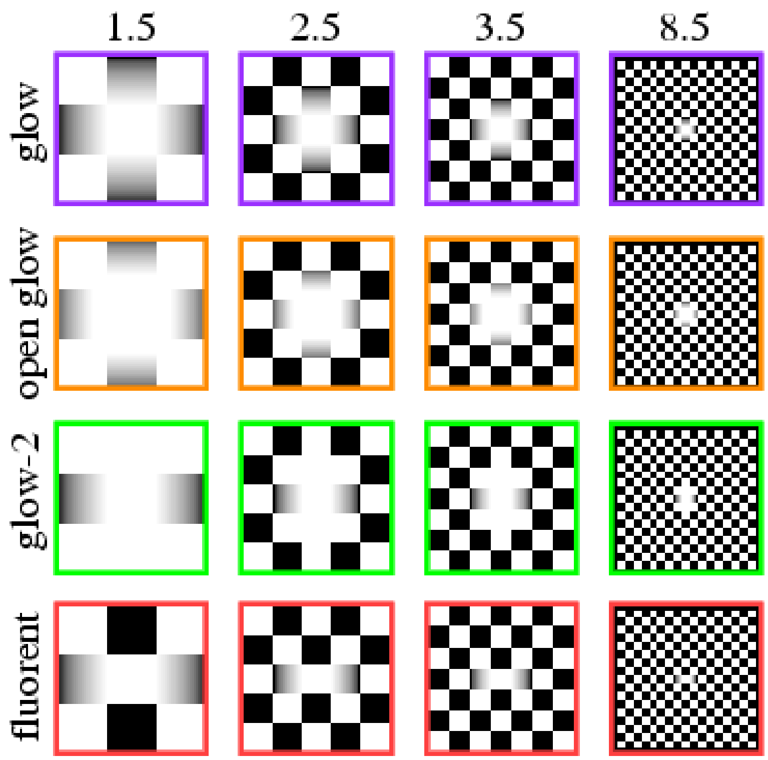


FIG. 4: **A glow parade.** The figure shows three modifications ("open glow", "glow-2", and "fluorent") of the original glare effect display shown in the first row ("glow") at four spatial frequencies of the chessboard carrier (number denoting columns correspond to cycles per image). Gradient representation of these images are shown in figure 7. The center square of each image appears as being light-emitting, albeit the strength of the effect seems to depend on display configuration and spatial frequency.

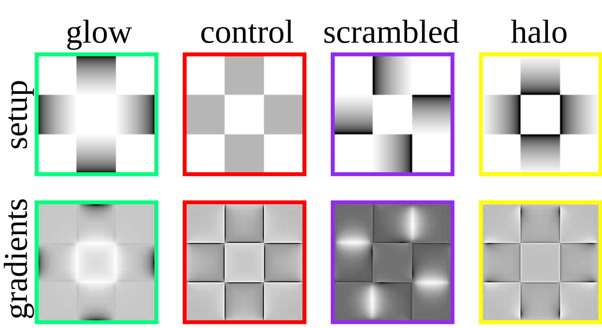
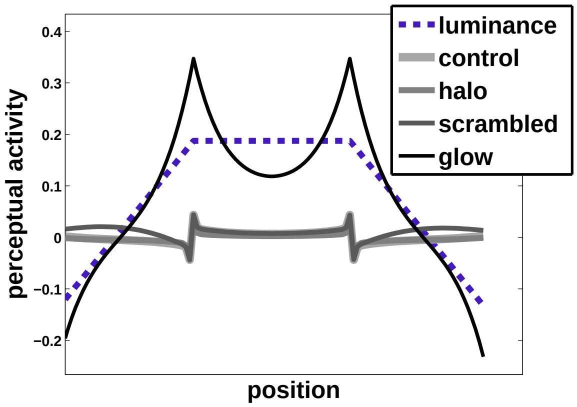


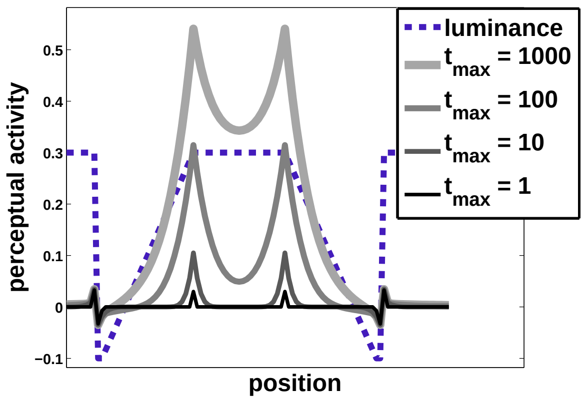
FIG. 5: **Setups.** The top row defines the four setups *glow*, *control*, *scrambled*, and *halo* as employed in the present study (setups are distinguished by *italic* letters). The definition follows the luminance displays as they were introduced in the study of [7]. Self-luminosity is only perceived for the *glow* setup, but in none of the other cases. Notice, however, the light Mach bands at the white end of the ramp for the *scrambled* setup (the Mach bands are reproduced as white lines in the gradient representations). The bottom row shows the corresponding gradient representations.

The corresponding gradient representation has low activity, with similar amplitudes of brightness and darkness. Due to the absence of brightness and darkness sources, no lateral spread of activity occurs, and activity across the central square is close to zero (as indicated by gray colors in figure 5, see also figure 6*a*). In the *scrambled* setup, again bright Mach bands (i.e., brightness sources) are created. However, the contour of each ramp, along which luminance increases, contrasts strongly with the central square. These contrasts are "non-gradients" and constitute barriers for the propagation of gradient activity. Thus, no brightness activity originating from the Mach bands can propagate into the central square, and no brightness enhancement of the latter occurs. The gradient representation that is created for the *halo* setup is similar to the *control* setup. Notice, however, that neither bright Mach bands nor activity gradients are created at the bright side of each ramp. This is due to a strong contrast with the domain boundary, as a consequence of the domain boundary conditions which were used for the simulation (c.f. [20] or [22]).

The predictions of the gradient system can be summarized as follows (c.f.figure 10). A target region is perceived as being light-emitting if in its gradient representation it is tagged with high brightness activity, despite of the absence of actual luminance gradients across that target. The target is filled in with brightness if *(i)* brightness



(a)



(b)

FIG. 6: **Profiles of gradient representations shown in figure 5.** **(a)** The curves correspond to horizontal profiles of the 2-D gradient representations shown in figure 5 (profiles show all columns for the center row of a 2-D display). Each curve thus represents a different setup as denoted by the legend. **(b)** Profile plots of gradient representations at different simulation times (see legend) for the second image of figure 4 (spatial frequency 2.5 cycles per image). Note the elevated gradient brightness activity (positive values) across the central square. At time 1, non-zero gradient activity is obtained only at Mach band positions, but not across the central square. However, during the generation of the gradient representation, the central square gets filled in with brightness. This filling-in effect occurs only for the *glow* setup, but not for any of the others. Curves representing luminance were rescaled independently for both plots (original luminance values ranged always from 0 to 1).

sources are located sufficiently close to it, and if *(ii)* no activity is annihilated because of the presence of drains or sinks nearby or across the target. Then, brightness can accumulate (i.e., activity grows in time across the target region), and finally gets much higher than darkness activity, such that luminosity is perceived (a strong excess of brightness over darkness). This situation is typically created by the presence of linear luminance gradients adjacent to the target. These predictions are examined further in the following section by introducing specific modifications of the original *glow* setup.

C. Modifications of the glare effect display and size effects

Figure 4 shows three modification of the original glare effect display which also lead to the perception of luminosity. The corresponding gradient representations are shown in figure 7.

Open glow. Each luminance ramp was shifted by 32% (of the square length in pixels) to the darker side, and the total ramp size was reduced to 75%. Still a glowing effect can be observed. The gradient system consistently predicts this effect – brightness of the ramp accumulates in the central part of the image, although activity propagation now takes place over a larger region than the central region of the original display, and despite of the target region being no longer tightly enclosed by the Mach bands.

Glow-2. A glow effect is also seen with only two luminance ramps. However, this effect is weaker because brightness activity can escape at the top and the bottom into the white regions adjacent to the target region.

Fluorent. The top and the bottom side of the central square is now enclosed by uniform black squares. The boundaries of each black square give rise to non-gradient inhibition, thus implementing activity drains at the central square (figure 11). Therefore, brightness enhancement should be weaker compared to the *glow-2* display. In fact, the sensation appears to be what has been described as “preluminous super white” [16] or “*fluorent*” [8].

Because all of the glow effects presented in this paper are induced by linear luminance ramps, and because Mach bands are attached to linear luminance ramps, the glow effects should also depend on ramp width or scale, respectively. The perceived strength of Mach bands is small for narrow ramps, large at ramps of intermediate size, and decreases again with broad ramps (“inverted-U”-behavior, [34]). Increasing the spatial frequency of the chessboard carrier decreases both the ramp width, and the size of the central square. Figure 4 illustrates the dependence of the perceived glowing strength on spatial frequency for 1.5, 2.5, 3.5, and 8.5 cycles per image. Although precise psychophysical data concerning this spatial frequency dependence are not (yet) available, some of the effects seem to be stronger at an intermediate frequency. The gradient system clearly suggests a relationship between carrier frequency and glow strength (figure 7). Notice, however, that the gradient system is not calibrated with respect to viewing distance, and maximum effects may be predicted at different spatial frequencies than perceived by humans when looking at figure 4.

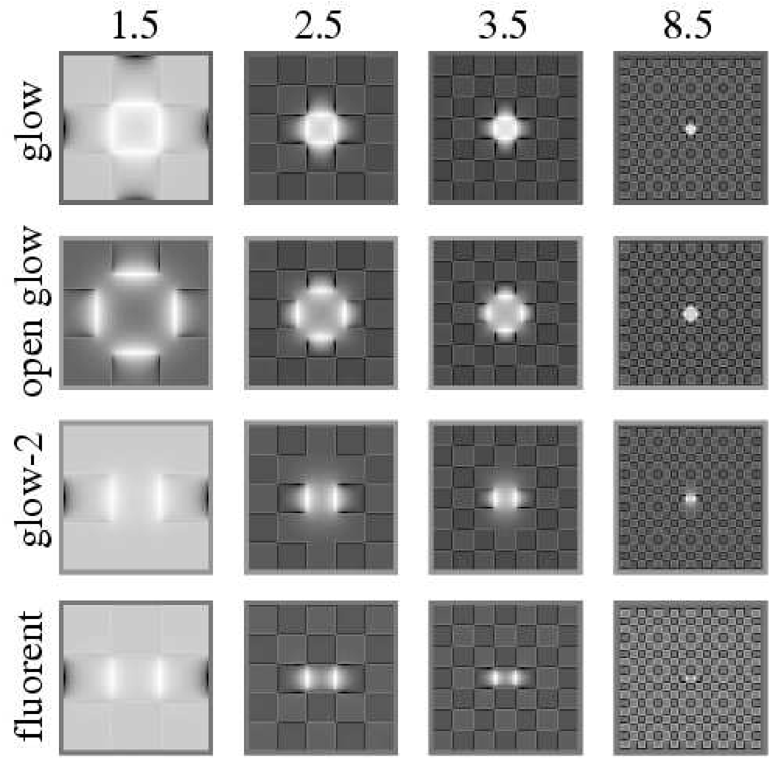


FIG. 7: **Gradient Representations for figure 4.** Each image has been normalized individually to improve visualization. Darkness activity of gradient representations corresponds to dark colors, and brightness activity to bright colors.

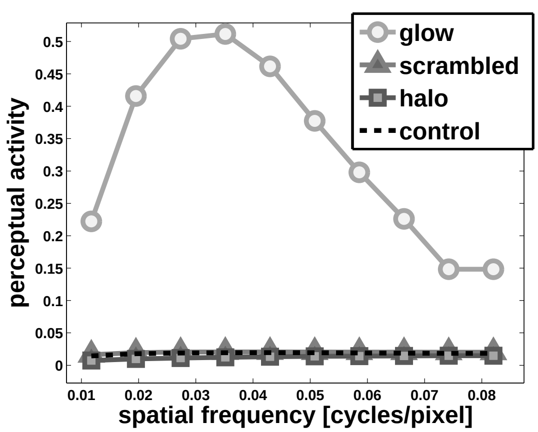
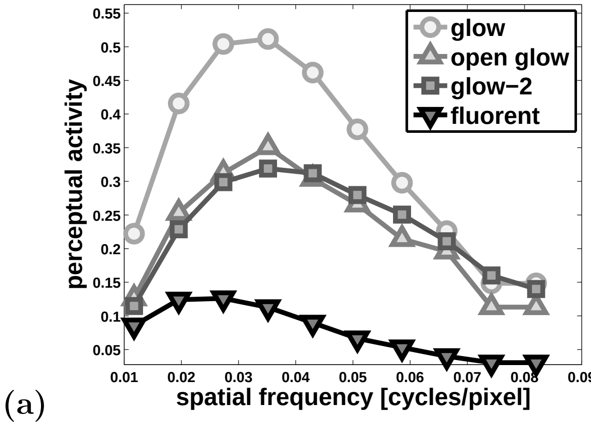


FIG. 8: **Varying spatial frequency (setups).** The curves show gradient activity averaged over the central square of the glare effect display for various spatial frequencies of the chessboard carrier. Each curve represent a different setup (legend – see figure 5). The gradient system predicts relative high activities across the central square only for the *glow* setup, where humans perceive the central square as being luminous.

In figure 8, the strength of glowing is quantified in terms of the mean gradient activity over the central square for different spatial frequencies of the chessboard carrier (see section III). A maximum effect is predicted for the *glow* setup, but no brightness enhancement of the target does occur for the setups *scrambled*, *halo*, and *control*. In figure 9, the strength of glowing is measured both by computing the mean activity over the central square (a) and the maximum (b). The glow display is predicted to produce the strongest effect (figure 10), and the fluorent display to produce the weakest (figure 11). The important result with these curves is the prediction of a maximum at some intermediate spatial frequency. Notice, however, that the curves shift along the ordinate depending on whether the spatial average across the central square was computed, or the maximum value was taken. This is because the central square is not filled in homogeneously with brightness activity, but gradient activity rather decreases towards the center of the central square (figure 6). This "bowing effect" is especially prominent with larger region sizes or at low spatial frequencies, respectively (cf. figure 7).

D. Glowing grays?

[42] reported the perception of "glowing grays" [39] in a psychophysical experiment where subjects first had to adjust the central square of a chessboard display until it was perceived as white (no luminance gradient was present in this display). Next, they were asked to adjust the central square of a second display until it was per-



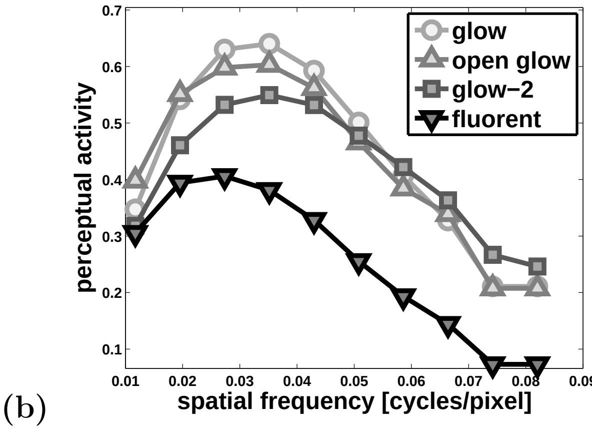


FIG. 9: **Varying spatial frequency (displays).** Both plots show the gradient activity of the central square for the different types of luminance displays shown in figure 4 with spatial frequencies indicated on the abscissa. Display types are denoted in the legend. For the open glow display, the central square region for measuring gradient activity had to be expanded by 32% to each side in order to capture the full effect. **(a)** The gradient activity is measured by spatial averaging activity values over the central square. **(b)** The maximum value of gradient activity over the central square was computed.

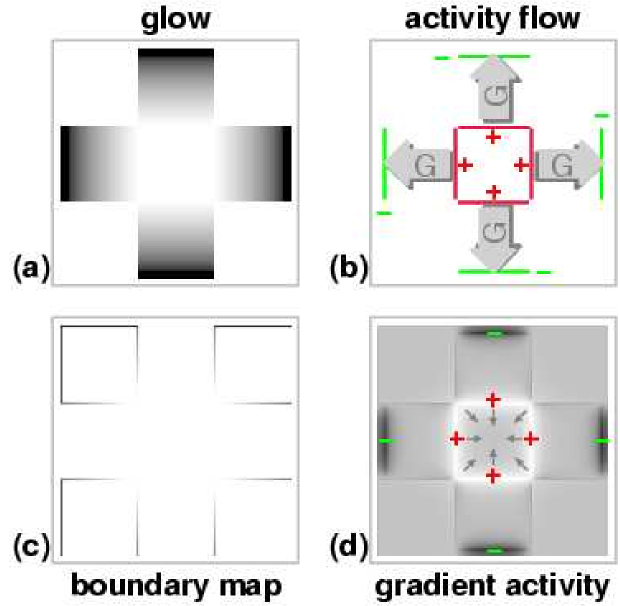


FIG. 10: **Why the glow display produces the strongest effect.** **(a)** The glow display (c.f. figure 4) **(b)** (Brightness) sources are designated with "+", and (brightness) sinks with "−". An activity gradient will form between sources and sinks: The arrows designated by "G" indicate the direction of gradient formation from increasing to decreasing perceived luminance. Notice that the central (or target) square is surrounded by four brightness sources. **(c)** The boundary map is equivalent to locations where non-gradient inhibition is active. It is assumed that surface representations are triggered there. No boundaries are present around the target square, and thus no non-gradient inhibition is produced. **(d)** Since brightness sources constantly generate activity, and no loss of activity occurs across the central square (due to the presence of a brightness sink or non-gradient inhibition), brightness activity can accumulate (small arrows; see also figure 6). Accumulated brightness over the target square is proposed to be associated with the perception of luminosity. Notice that the activity gradients do not extend into the four white squares in the corners because of non-gradient inhibition.

ceived to glow (the image for their second display was identical to the *glow* setup in figure 5). The experiment was carried out for three different luminance levels of the (originally white) squares in the corners of the display (= background luminance). The authors observed that subjects did not adjust the central square of the *glow* display to white. In other words, it was already perceived as glowing at some gray level.

Figure 12 shows the dependence of gradient brightness on the luminance level of the central square. Notice that the curve for the the *glow* setup reveals an abrupt increase between luminance levels 0.4 and 0.5. In other words, the gradient system reveals a threshold behavior[47], where gradient brightness strongly increases with the respect to the curves for the other setups *scrambled*, *halo*, and *control*. After the step-like increment, the curve shows an approximately linear dependence on the luminance level of the central square. At luminance ≈ 0.9, the curve reveals a moderate increase in slope.

Because only the *glow* setup leads to the sensation of glow, and because before the step-like increment gradient brightness is approximately the same as with the other three setups (which are not associated with the perception of glow), this step-like increment in fact corresponds to an absolute threshold for the central square to be perceived as light-emitting. Moreover, because the step-like increment occurs between luminance levels 0.4 and 0.5 which is associated with mid-gray, the gradient system indeed predicts the occurrence of "glowing grays".

The background luminance level influences in retinal adaptation, and also in lightness anchoring. The present version of the gradient system, however, does neither incorporate mechanisms for adaptation, nor does it incorporate interactions with surface representations (or light-

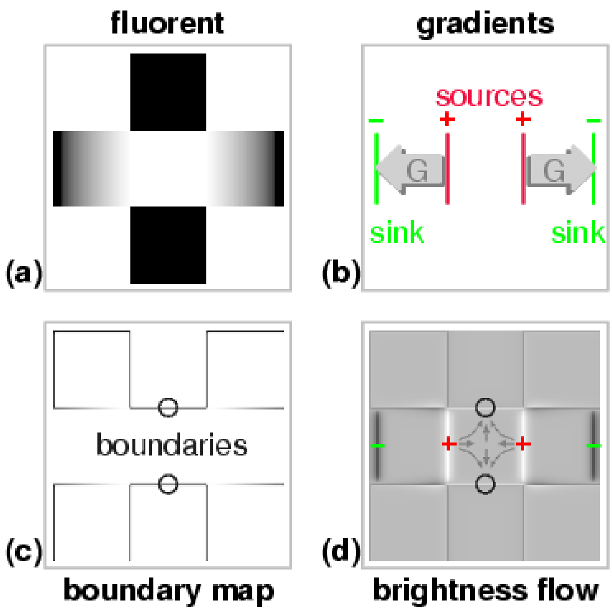


FIG. 11: **Why the fluorent display produces the weakest effect. (a)** The fluorent display (c.f. figure 4) **(b)** In comparison to the glow display (previous figure), only two activity gradients will be generated (arrows designated with "G"). **(c)** Apart from two brightness sources, the central square is now also flanked by two contours ("◯") giving rise to non-gradient inhibition. As explained in the last paragraph of section II B, non-gradient inhibition acts like a passive drain, for both brightness sources and brightness sinks. **(d)** Activity propagates from brightness sources "+" into the central square, but its accumulation is less than with the glow display (figure 10) because it gets annihilated at contours "◯" (small arrows). Therefore, the target square of the fluorent display will appear less luminous than the target of the glow display.

ness computations).

E. Influence of the luminance ramp

In [41], subjects were asked to adjust the height of the luminance ramps surrounding the central square of a glare effect display (= first image of figure 5) while the central square was always held fixed at white. This procedure was repeated for different levels of the four (originally white) squares in the corner of the display (= background luminance). The authors found that the threshold for perceiving the central square as glowing (= luminosity threshold) increased with increasing background luminance in precisely the same way as the curve for the *glow* setup in figure 13 (see figure 3 in [41]). However, figure 13 does not show luminosity threshold versus background luminance, but gradient activity of the central square versus the upper ramp luminance. So why is it that both curves are so similar?

The curve of figure 13 (*glow* setup) shows the predicted sensation of luminosity given some ramp luminance level (as illustrated by figure 1 in [42]). The results from [41], demonstrate that the luminosity threshold increases as a function of background luminance. When comparing their results to the predictions of the gradient system, it therefore seems that the background luminance level sets a baseline level below of which luminosity cannot be perceived. This idea is equivalent to putting horizontal lines in figure 13, with an intercept proportional to background luminance. Therefore, to perceive luminosity, the upper ramp luminance has to be adjusted such that gradient activity is just above the horizontal line. And this is what is shown in figure 1 of [41].

V. DISCUSSION

A recent psychophysical study from [7], assigned feature status to luminance gradients. Accordingly, here I studied the predictions of the gradient system for luminance displays which appear self-luminous. The gradient system is an instantiation of a recently proposed theory about how luminance gradients are segregated from images, and how representations of luminance gradients are generated [20, 22].

Here I showed that gradient representations have higher activity levels across the central square in those displays that are associated with the sensation of glow (*glow* setup, figure 5). Conversely, gradient activity is low in displays which are not perceived as light-emitting (setups *control*, *halo*, *scrambled*). My results therefore support the conjecture from [42] that luminance gradients play a crucial role in luminosity perception.

Three modifications of the glare effect display were devised (figure 4) to put to the test the following predictions of the gradient system (figure 7): *(i)* gradient activity accumulates in the central square what predicts a corresponding enhancement in perceived brightness (original "glow" display); *(ii)* if the central square is enclosed by only two luminance ramps ("glow-2" display), then gradient activity spreads into the open region, but luminosity should still be perceived; *(iii)* if the central square is delineated by sharp contrasts ("fluorent" display), then drains for brightness activities are created which should lead to a reduction of the glow effect, and finally *(iv)* as gradient activity spreads laterally originating from brightness sources (which are perceived as bright Mach bands surrounding the central square), the perceived luminosity should depend on the size of the target region or the spatial frequency of the chessboard carrier, respectively ("open glow" display, and figure 8 & figure 9).

For the luminance displays considered in this paper, the gradient system predicts a threshold behavior above which the central square is perceived as being light-emitting (the step-like change in figure 12): Light emission is already predicted at intermediate luminance values ("glowing grays"). In addition, the gradient system provides a consistent explanation of the results from [41]

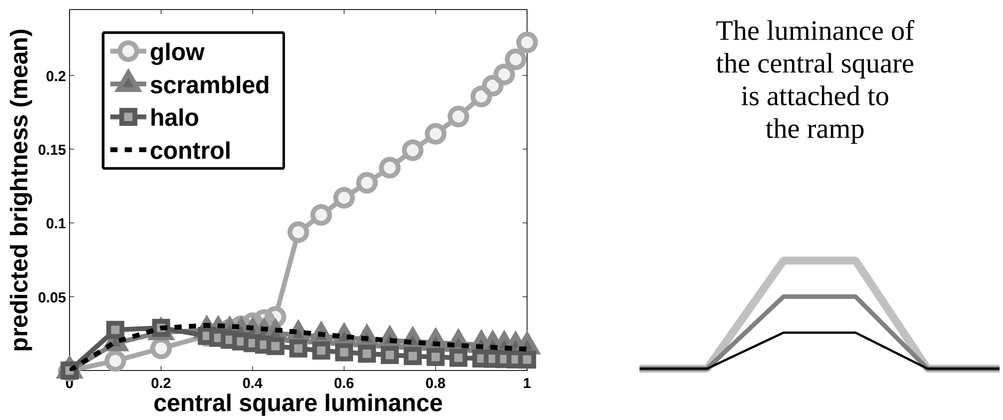


FIG. 12: **Varying the intensity of the central square.** The curves show the predicted gradient brightness activity as a function of the luminance of the central square (sketch) for the setups of the glare effect display (1.5 cycles per image, cf. first image in figure 4). The gradient brightness associated with the *glow* setup abruptly increases between intensity levels 0.4 and 0.5 (= step-like increment), whereas a relatively weak dependence on luminance is predicted for the setups *scrambled*, *halo*, and *control*. Similar curves are obtained by plotting the maximum activity of the central square. The location of the step-like increment does not depend significantly on the spatial frequency of the chessboard carrier.

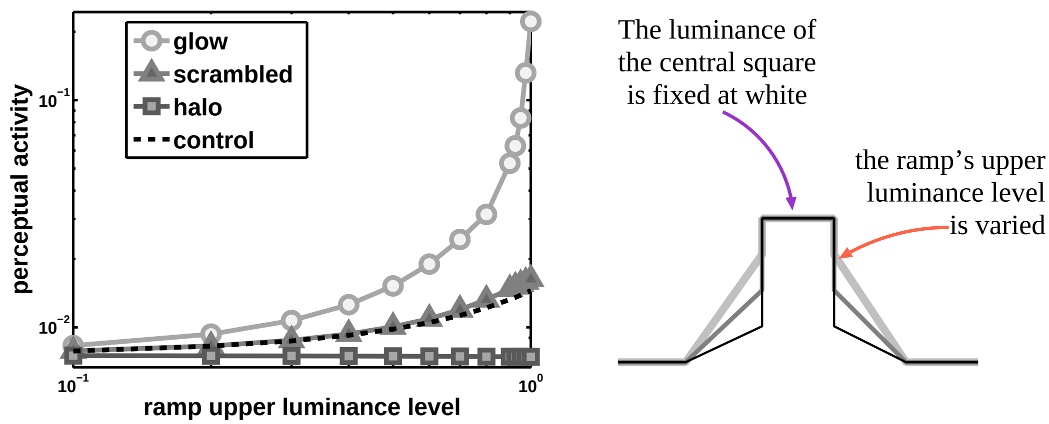


FIG. 13: **Varying intensity.** The luminance of the central square of the chess ramp display was held fixed at white, and the upper knee-point of the ramp was set to different luminance values from black (corresponding to an ordinary chessboard without luminance ramps) to white (corresponding to the glare effect display). The shape of the curve for the *glow* setup matches well the psychophysically measured curve shown in figure 3 of [41] (but see text for further details).

(compare their figure 1 with my figure 13).

A. Gradient representations, lightness, and brightness

The gradient system was proposed as one part of three, in parallel acting processing streams, for generating texture representations[48] and surface representations (see [19, 21]). Although it is clear that surface representations and gradient representations have to interact at some level in the object recognition hierarchy (e.g., in order to derive shape from shading), it is not clear how such interactions could be implemented at an early level in the visual system.The original idea was that whenever odd-symmetrical and sharply bounded contrasts are present in an image, the corresponding information triggers the generation of surface representations by a filling-in process. By contrast, the presence of blur or soft contrasts trigger representations of luminance gradients (figure 14 and 15).

The present study suggests that the perception of luminosity is associated with gradient representations, but not with surface representations. But then, surface representations can be directly related to perceived reflectance. Otherwise expressed, the perceptual correlate of surface representations is lightness. Reflectance describes a property of surfaces which has the value zero if the surface absorbs all light (and thus appears black),

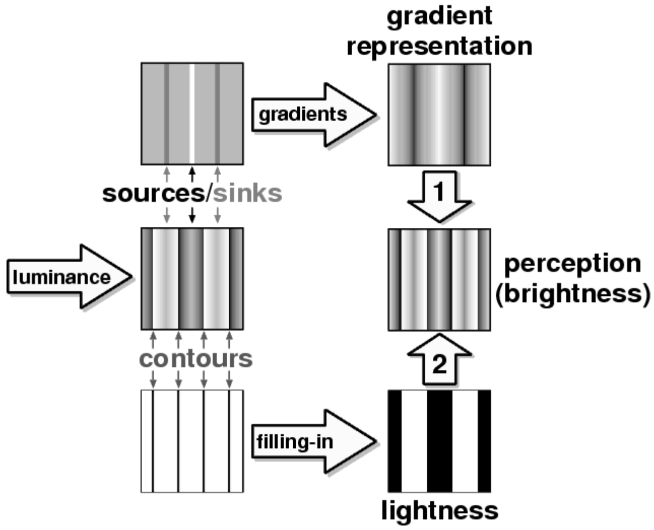


FIG. 14: **How gradient representations relate to the filling-in framework.** A "notch grating" luminance pattern ("luminance" arrow) is used to illustrate conceivable interactions between lightness computations and gradient representations. Contours are detected at the step-like luminance changes, what triggers a filling-in process for computing surface lightness ("filling-in" arrow; [6, 10]). Filling-in processes were suggested as a theoretical mechanism to implement invariance properties for surface representations, for example "discounting the illuminant" to implement lightness constancy (e.g., [14, 15, 30, 31, 32]). As we perceive lightness constancy, but at the same time also smooth changes in luminance [36], surface lightness and gradient representations need to interact (arrows "1" & "2"). This interaction finally is proposed to result in brightness perception.

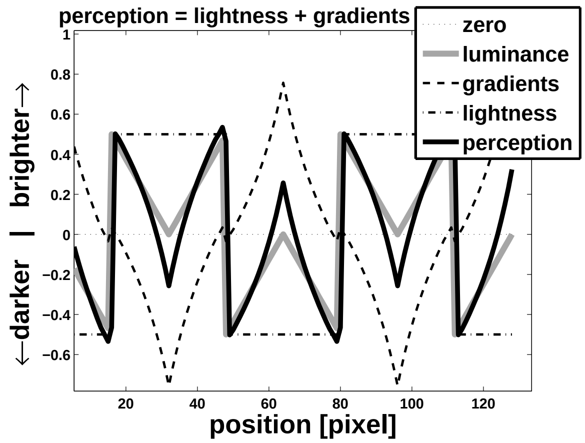


FIG. 15: **Gradient and surface representations.** The curves illustrate a possible mechanism for the interaction of gradient representations with surface representations. Each curve shows a profile plot (all columns for a fixed row) of the images shown in figure 14. The brightness prediction was computed by assuming a simple linear interaction between ON- and OFF-channels of surface and gradients (figure title), yet it correctly predicts that the faint lines in the center of the dark step are perceived brighter than the faint lines of the bright step, albeit both lines have the same luminance level.

and the value one if the surface reflects all light. Gray levels are represented by intermediate reflectance values. Ideally, lightness should follow reflectance. However, if luminosity effects were explained in terms of reflectance, this would imply that reflectance values were bigger than one, because the surface would emit more light than it actually could reflect.

Furthermore, lightness constancy implies that reflectance is perceived as approximately constant despite of variations in illumination conditions. Lightness constancy seems also not to be affected significantly by the presence of specular highlights on surfaces [36]. Gradient representations therefore are supposed to contain all surface information that otherwise would affect lightness constancy and thus object recognition. Taken together, luminosity is not perceived on the lightness scale, but on the brightness scale. Brightness comprises all perceptual aspects of a scene, including lightness and luminosity. What happens, however, if surface representations and gradient representations are simultaneously triggered for one and the same region? This situation occurs, for example, with a luminance staircase giving rise to Chevreul's illusion (e.g., figure 8 in [20]). Because Chevreul's illusion commonly is not described as being light emitting, it seems that the presence of surface representations weakens the perceptual impact of gradient representations in terms of brightness.

Similarly, for the notch grating stimulus, surface representations and gradient representations are simultaneously triggered (figure 14). More precisely, each step-like change in luminance triggers a surface representation, and the faint lines centered at each step constitute the sources and sinks for producing gradient representations (see arrows with corresponding labels in figure 14).

A possible mechanism for creating surface representations are so-called filling-in processes [6, 10], which serve to assign perceptual properties (e.g., lightness, color, or depth) to object surfaces (e.g., [14, 15, 30, 31, 32]). As a result, surfaces are rendered invariant against smooth changes in the corresponding stimulus attribute. For example, smooth luminance gradients are discounted in surface representations, and in this way lightness constancy is achieved. Nevertheless we still perceive luminance gradients, what leads to the question how gradient representations interact with surface representations.

Consider the *scrambled* setup (figure 5). Although Mach bands are perceived, no brightness enhancement of the four white squares in the corners of the display seems to take place. For each of these squares, a gradient representation is triggered at one side (where the Mach bands are observed), and a surface representation is triggered at the other side (at the lower or dark end of

the luminance ramp).
Similarly, the configuration that has been examined with figure 13 corresponds to a situation where a sharply-bounded contrast concurs with a ramp (see also figure 1 in [42]). But then again, a surface representation (giving rise to lightness activity) and a gradient representation are generated at the same time for the central square. Depending on whether the one or the other representation has higher activity, one perceives luminosity (only gradient activity), super white (gradient activity and lightness activity), or only ordinary "white" (i.e. only lightness activity).
Taken together, these observations support two conclusions. First, the mechanism for triggering surface or gradient representations does not operate in a "all-or-none" fashion, but rather operates continuously. Second, the concurrent presence of a surface representation and a gradient representation for a region may reduce or even abolish the perception of luminosity. Notice that both conclusions are not mutually exclusive.

B. Competing models for luminosity perception

I briefly discuss three different models in turn which could in principle account for the perception of luminosity.
[37] suggested an extension to the Retinex theory [25, 26] such that light sources can be detected in achromatic Mondrian displays. The idea is to compute the gradient ratio and the intensity ratio between adjacent surfaces. If the ratios are different, then one of the areas is a light source (see [41] for a more detailed discussion of this model with respect to the glare effect display). Ullman's model thus links luminosity to lightness computations.
By measuring the intensities of surfaces, [3], and [4], could establish a relationship between surface area and the luminance value at which the surface appeared as being luminous (= luminosity threshold). They found that *(i)* a 17-fold increase in the surface area lead to a 3-fold increase in the luminosity threshold, and *(ii)* for a surface to be perceived as light-emitting, its intensity must be ≈ 1.7 times larger than the intensity of a non-luminous, white surface (under identical illumination conditions). To illustrate, consider a simple display where a surface is divided into a dark region and a lighter region. The luminance ratio of both areas is held constant. Let the dark region initially be small, and now gradually increase its size with respect to the lighter region. In this case, the lighter surface is anchored at white according to the "*Highest-Luminance-As-White*" (HLAW) rule [39], and the lightness of the darker region will be determined by the luminance ratio with the lighter region. Lightness will be constant until the relative size of the dark region grows bigger than the relative size of the lighter region: the *area rule* applies and perceptual changes are produced. Once the darker region is bigger, it appears lighter and lighter, until, according to the highest luminance rule, it is anchored at white (as it approaches 100% size). However, what happens with the lighter region? At first, as the dark region is perceived lighter, it remains at white. Thus, a compression of lightness occurs, despite of the luminance ratio being held constant. Gradually, however, the white region gets "whiter than white" (or super white, or fluorent). Finally, as the dark region approaches 100% and thus white, the white region is "forced to relinquish its white appearance and take on the appearance of self-luminosity" (see [11], p.803). However, as admitted by Gilchrist and colleagues, their findings apply only to simple Ganzfeld displays, and yet needs to be studied with more complex displays (p. 802). Because anchoring is related to lightness and thus to surface representations, anchoring is not considered by the gradient system in its present version. Consequently, no area rule applies to the gradient system. The present results suggest that gradient representation in the absence of concomitant surface representations accounts for the perception of luminosity. Note that a luminosity threshold is revealed as a function of the luminance of the central square (figure 12). The location of the threshold does not depend on the spatial frequency of the carrier (that is, on the size of the central square). However, the luminosity threshold of the gradient system does not depend on the luminance of the other squares in the display, and therefore is different from the luminosity threshold (i.e., the factor 1.7) measured by [3].
Furthermore, it is not clear how the area rule applies to the open glow display of figure 4: the apparent glow area is increased with respect to the glow display, but this does not seem to compromise the perception of self-luminosity.
The observation that the lighter region appears self-luminous if it is sufficiently small with respect to the dark region could in principle be explained with the formation of luminance gradients at the retina (e.g., "halos", [42]) Such gradients may be produced at small and bright stimuli embedded in a darker background due to increased pupil size and the major part of the retinal array being adapted to the darker background [1, 35].
The computational model of [12, 13, 17] treats the generation of surface representations in the context of the anchoring theory of lightness perception [11]. Surface representations are generated by filling-in mechanisms. Anchoring of perceived reflectance follows a modification of the HLAW rule [39], which is the "*Blurred-Luminance-As-White-Rule*" (BHLAW). The modification overcomes problems like that "a point-like small bright patch on the visual field will be dealt with the same as a large whiteboard occupying most of the visual field". Thus, instead of looking simply for the highest luminance value in an image and anchoring it at white, the BHLAW rule suggests to anchor the highest value in a low-pass filtered version of the image at white (where with "image" a filled-in surface representations is meant). The percep-

tion of luminosity occurs when an image region which has the highest filled-in activity is smaller than the size of the blurring kernel. This mechanism for producing luminosity effects is therefore different from the gradient system, because it again measures luminosity on the lightness scale. Luminosity effects were demonstrated by the BHLAW-model with the "Double Brilliant Illusion" [5], which creates a sensation of glow by using luminance gradients analogously to the glare effect display.
The BHLAW model's overall behavior follows the anchoring theory and area rule as described above. An important difference between the BHLAW model and the gradient system is that the former uses various resolution levels or scales for the filling process (although not for the blurring kernel for implementing the anchoring process).

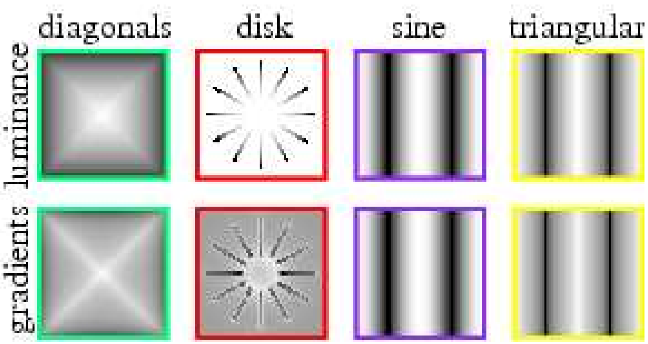


FIG. 16: **More examples for luminance gradients.** The second row shows the gradient representations obtained with the images from the first row. From left to right: the glowing diagonals of a luminance pyramid are predicted by the gradient system. The brightness enhancement of an Ehrenstein Disk with an overlaid luminance gradient is predicted. A sine wave grating as an example of a nonlinear luminance gradient (doesn't the white stripe in the middle appear to glow?). A triangular-shaped luminance profile reveals bright and dark Mach bands effects (horizontal stripes), which are also predicted by the gradient system.

C. Conclusions

Recent psychophysical data concerning the luminosity effect suggest that luminance gradients are a perceptual feature just like, for example, orientation, contrast or color [7]. Accordingly, in the present paper, a recently proposed theory about the processing of luminance gradients has been evaluated in the context of luminosity perception. The gradient system suggests how luminance gradients are processed by the visual system at an early level, and how they can give rise to perception of luminosity. As gradient representations are thought to be complementary to surface representations (i.e., lightness computations), possible interactions between both representations were discussed. Although the gradient system is already successful at explaining several brightness illusions in terms of luminance gradients (see also figure 16), mechanisms which address the interactions with surface representations and texture information need to be incorporated. However, the precise nature of such mechanisms have yet to be established by corresponding studies in fields like neurophysiology or psychophysics.
So, why are items displayed on a (light-emitting) computer screen are not perceived as self-luminous? The answer is that there are no luminance gradients created by the (light-emitting) pixels which could trigger gradient representations. Only surface representations are produced, and thus the displayed items are perceived on the lightness scale.

Acknowledgments

This work was supported by the *Juan de la Cierva* program of the Spanish government (BKC-IYK-6707), and the the MCyT grant SEJ 2006-15095. The author likes to thank Fred Kingdom and two reviewers from *Vision Research* for their help in improving the first drafts. The present preprint is an extended version of the "official" *Vision Research* manuscript.

[1] Bettelheim, F. & Paunovic, M. (1979). Light scattering of normal human lens. *Biophysical Journal*, 26, 85–99.
[2] Bloj, M., Kersten, D., & Hurlbert, A. (1999). Perception of three-dimensional shape influences colour perception through mutual illumination. *Nature*, 402, 877–879.
[3] Bonato, F. & Gilchrist, A. (1994). The perception of luminosity on different backgrounds and in different illuminations. *Perception*, 23, 991–1006.
[4] Bonato, F. & Gilchrist, A. (1999). Perceived area and luminosity threshold. *Perception & Psychophysics*, 61, 786–797.
[5] Bressan, P., Mingolla, E., Spillmann, L., & Watanabe, T. (1997). Neon color spreading: a review. *Perception*, 26, 1353.1366.
[6] Cohen, M. & Grossberg, S. (1984). Neural dynamics of brightness perception: Features, boundaries, diffusion and resonance. *Perception and Psychophysics*, 36, 428–456.
[7] Correani, A., Scott-Samuel, N., & Leonards, U. (2006). Luminosity - a perceptual feature of light emitting objects? *Vision Research*, 46, 3915–3925.
[8] Evans, R. (1959). Fluorescence and gray content of surface colors. *Journal of the Optical Society of America*, 49, 1049.
[9] Fowlkes, C., Martin, D., & Malik, J. (2007). Local figure-ground cues are valid for natural images. *Journal of Vision*, 7(8), 1–9.
[10] Gerrits, H. & Vendrik, A. (1970). Simultaneous contrast,

filling-in process and information processing in man's visual system. *Experimental Brain Research*, 11, 411–430.

[11] Gilchrist, A., Kossyfidis, C., Bonato, F., Agostini, T., Cataliotti, J., Li, X., Spehar, B., Annan, V., & Economou, E. (1999). An anchoring theory of lightness perception. *Psychological Review*, 106(4), 795–834.

[12] Grossberg, S. & Hong, S. (2003). Cortical dynamics of surface lightness anchoring, filling-in, and perception (abstract). *Journal of Vision*, 3(9), 415a.

[13] Grossberg, S. & Hong, S. (2006). A neural model of surface perception: Lightness, anchoring, and filling-in. *Spatial Vision*, 19(2-4), 263–321.

[14] Grossberg, S. & Pessoa, L. (1998). Texture segregation, surface representation, and figure-ground separation. *Vision Research*, 38, 2657–2684.

[15] Grossberg, S. & Todorović, D. (1988). Neural dynamics of 1-d and 2-d brightness perception: A unified model of classical and recent phenomena. *Perception and Psychophysics*, 43, 241–277.

[16] Heinemann, E. (1955). Simultaneous brightness induction as a function of inducing- and test-field luminances. *Journal of Experimental Psychology*, 50(2), 89–96.

[17] Hong, S. & Grossberg, S. (2004). A neuromorphic model for achromatic and chromatic surface representation of natural images. *Neural Networks*, 17(5-6), 787–808.

[18] Jospeh, J., Chun, M., & Nakayama, K. (1997). Attentional requirements in a 'preattentive' feature search task. *Nature*, 387, 805–807.

[19] Keil, M. (2003). *Neural Architectures for Unifying Brightness Perception and Image Processing*. PhD thesis, Universität Ulm, Faculty for Computer Science, Ulm, Germany. http://vts.uni-ulm.de/doc.asp?id=3042.

[20] Keil, M. (2006). Smooth gradient representations as a unifying account of Chevreul's illusion, Mach bands, and a variant of the Ehrenstein disk. *Neural Computation*, 18(4), 871–903.

[21] Keil, M., Cristóbal, G., Hansen, T., & Neumann, H. (2005). Recovering real-world images from single-scale boundaries with a novel filling-in architecture. *Neural Networks*, 18(10), 1319–1331.

[22] Keil, M., Cristóbal, G., & Neumann, H. (2006). Gradient representation and perception in the early visual system - a novel account to Mach band formation. *Vision Research*, 46, 2659–2674.

[23] Kennedy, J. (1976). Sun figure: an illusory diffuse contour resulting from an arrangement of dots. *Perception*, 5, 479–481.

[24] Kersten, D., Knill, D., Mamassian, P., & Bülthoff, I. (1996). Illusory motion from shadows. *Nature*, 379, 31.

[25] Land, E. (1977). The retinex theory of color vision. *Scientific American*, 237, 108–128.

[26] Land, E. & McCann, J. (1971). Lightness and retinex theory. *Journal of the Optical Society of America*, 61, 1–11.

[27] Leonards, U., Troscianko, T., Lazeyras, F., & Ibanez, V. (2005). Cortical distinction between the neural encoding of objects that appear to glow and those that do not. *Cognitive Brain Research*, 24, 173–176.

[28] Mach, E. (1865). Über die Wirkung der räumlichen Verteilung des Lichtreizes auf die Netzhaut, I. *Sitzungsberichte der mathematisch-naturwissenschaftlichen Klasse der Kaiserlichen Akademie der Wissenschaften*, 52, 303–322.

[29] Mingolla, E. & Todd, J. (1986). Perception of solid shape from shading. *Biological Cybernetics*, 53, 137–151.

[30] Neumann, H., Pessoa, L., & Hansen, T. (2001). Visual filling-in for computing perceptual surface properties. *Biological Cybernetics*, 85, 355–369.

[31] Pessoa, L., Mingolla, E., & Neumann, H. (1995). A contrast- and luminance-driven multiscale network model of brightness perception. *Vision Research*, 35(15), 2201–2223.

[32] Pessoa, L. & Neumann, H. (1998). Why does the brain fill-in? *Trends in Cognitive Sciences*, 2, 422–424.

[33] Ramachandran, V. (1988). Perception of shape from shading. *Nature*, 331, 163–166.

[34] Ross, J., Morrone, M., & Burr, D. (1989). The conditions under which Mach bands are visible. *Vision Research*, 29(6), 699–715.

[35] Simpson, G. (1953). Ocular halos and coronas. *British Journal of Ophthalmology*, 37, 450–486.

[36] Todd, J., Norman, J., & Mingolla, E. (2004). Lightness constancy in the presence of specular highlights. *Psychological Science*, 15(1), 33–39.

[37] Ullman, S. (1976). On visual detection of light sources. *Biological Cybernetics*, 21, 205–212.

[38] von der Malsburg, C. (1995). Dynamic link architecture. In M. Arbib (Ed.), *The Handbook of Brain Theory and Neural Networks* (pp. 329–331). Cambridge, Massachusetts: The MIT Press.

[39] Wallach, H. (1948). Brightness constancy and the nature of achromatic colors. *Journal of Experimental Psychology*, 38, 310–324.

[40] Zavagno, D. (1999). Some new luminance-gradient effects. *Perception*, 28, 835–838.

[41] Zavagno, D. & Caputo, G. (2001). The glare effect and the perception of luminosity. *Perception*, 30, 209–222.

[42] Zavagno, D. & Caputo, G. (2005). Glowing greys and surface-white: the photo-geometric factors of luminosity perception. *Perception*, 34, 261–274.

[43] In [20], and [22], a simplified circuit is used to this end, which detects contours without using orientation-selective operators.

[44] For the sake of simplicity, ON- and OFF-channels interact directly for generating the gradient representations. The channels are distinguished by their respective sign, where information from the ON-channel has a positive sign, and information from the OFF-channel corresponds to negative values. See [20], p. 882 for more details.

[45] In [20] and [22], sources and sinks were simply defined as retinal ON plus gradient ON, and retinal OFF plus gradient OFF, respectively. These "static" sources and sinks are identical to the dynamically created ones if an input image contains only smooth changes in luminance, but no step-like changes.

[46] The gradient systems makes symmetrical predictions for brightness and darkness, and therefore produces analogous results for inverse displays (darkness enhancement when the central square is black, and the ramps terminate with black at the central square). I put the terms "perceived brightness / darkness" in quotes because brightness is "perceived luminance" and thus already refers to a perceptual variable.

[47] I verified that the step indeed corresponds to a threshold by repeating the simulations by choosing smaller increments of luminance. The step always appeared no matter how small the luminance increments were chosen.

[48] "Texture" in this context means fine-grained and even-

symmetric contrast features.